HEP Theory
Lattice Activities & Plans

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BROOKHAVEN NATIONAL LABORATORY

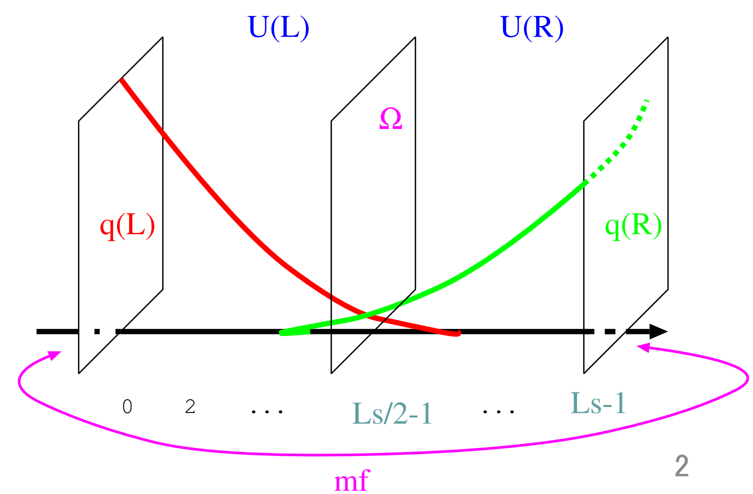
RIKEN BNL Research Center

Lattice Gauge theories

- True first-principles non-perturbative computations
- Indispensable bridge between experiment and theory, allowing new physics to be discovered. A part of precision frontier.
- Symmetries are key ingredients (gauge symmetry, chiral symmetry)

Domain-Wall quarks
good chiral symmetry
small unphysical mixings
- Small discretization error
- simple chiral extrapolations
- Unitary

- LGT and BNL
- '79 Lattice Gauge simulation [M. Creutz]
- '83- Electro Weak Matrix Element [Bernard & Soni,….]
- '97- Domain-Wall Fermions (DWF) Nf=0 quenched [Blum & Soni]
- '99- Riken-BNL-Columbia [RBC]
- '02- DWF Nf=2 up, down quarks [RBC]
- '05- DWF Nf=2+1 up, down, strange quarks [RBC-UKQCD]
- '10 DWF Nf=2+1, continuum limit [RBC-UKQCD]



RIKEN RICC ('09) ~ 110 Tflops peak

QCDOC('05) @Edinburgh~ 10Tflops peak

HEP Lattice at BNL

US Universities
Columbia
Connecticut

RIKEN-BNL
Research
Center

UKQCD
Univ. Edinburgh
Univ. Southampton

IBM

HEP Theory

FNAL/MILC

USQCD

NYCCS
CCS/ITD

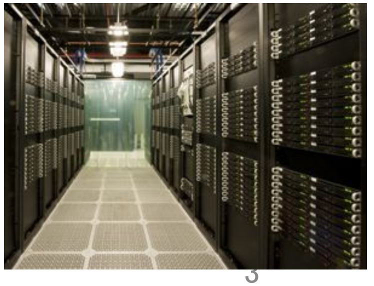
HotQCD

QCDOC('05) ~ 10Tflops peak

NYBlue('07)~ 130 Tflops peak

Intrepid ('08) ~560 Tflops peak

FNAL/Jlab ~ 160 Tflops peak



Organization

- BNL HEP Theory
  M. Creutz, TI, C. Jung*,
  A. Soni, R. Van de Water,
  O. Witzel*,
  R. Arthur, T. Kawanai¥, T. Misumi¥
  (* SciDAC, ¥ JSPS)

- RIKEN BNL Columbia (RBC) Collaboration (1998-)
  - RIKEN-BNL Research Center
    1.5 fellows, 2 PostDocs,
    3 long-term visiting scientists
  - Columbia University
    2 faculty, 2 PostDocs,
    8 Students
  - University of Connecticut
    1 faculty, 2 PostDocs, 2 Students

  Harvard, Yale,
  Virginia (Google), Regensburg

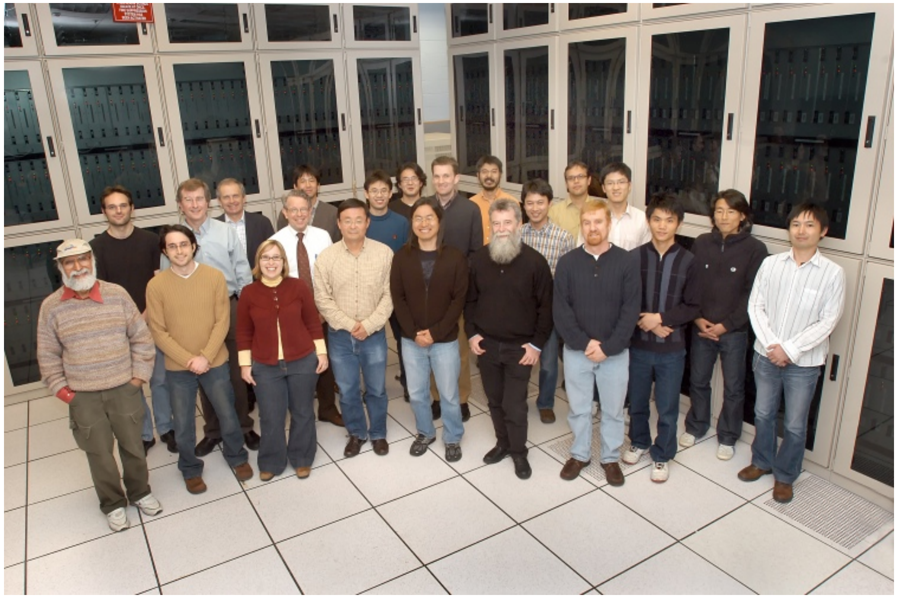
16 current students,
~20 PhD theses since 2005

- + UKQCD Collaboration (2005-)
  - Univ. of Edinburgh
    5 faculty, 1 fellows, 1 staff,
    2 PostDocs, 4 students
  - Univ. of Southampton
    2 faculty, 1 Postdoc, 2 students

  CERN,Julich

- + JLQCD (planned since 2010)
  - KEK, Tsukuba & Osaka Univ

(# of personnel: accumulation of last 3 years)



Synergy with RIKEN BNL Research Center

- RBRC
  T.D. Lee   1997-2002
  N.P. Samios 2003-
  - Lattice
  - Nuclear Theory
  - Experiment
  - Renewing MOU with BNL for JFY 2012-2017
- Synergy with HEP Theory group
  - Three generations of RBRC computers for Lattice

    QCDOC, the prototype of IBM's Blue Gene series, was a seed for USQCD's LQCD
  - Joint Fellows with Universities/Labs
  - Various PostDocs (in-house, RIKEN grants….)
  - Junior Research Associate (Students)
  - Produced a lot of tenured faculty in US, Japan and Europe.

    Tenured faculty: 29 (theory) + 15 (exp)
    out of 24 (theory)+15 (exp) fellows and 30(theory)+19(exp) PostDocs.

BROOKHAVEN NATIONAL LABORATORY

RIKEN BNL Research Center

Menu of Lattice Activities & Plans

- Formal study
- QCDCQ
- Ensemble Generation & Algorithm

  ensemble is publically available for US & international community

[Van de Water's talk]

- Pion Kaon Weak Matrix Elements
  B_K
  Im (A_2) and Re(A_2)
  Re(A_0)

  Im (A_0)

  K_L-K_S mass difference and
  long distance contribution to ε_K

- B- and D- meson Weak Matrix Elements

  Static limit Quark

  Relativistic Heavy Quark

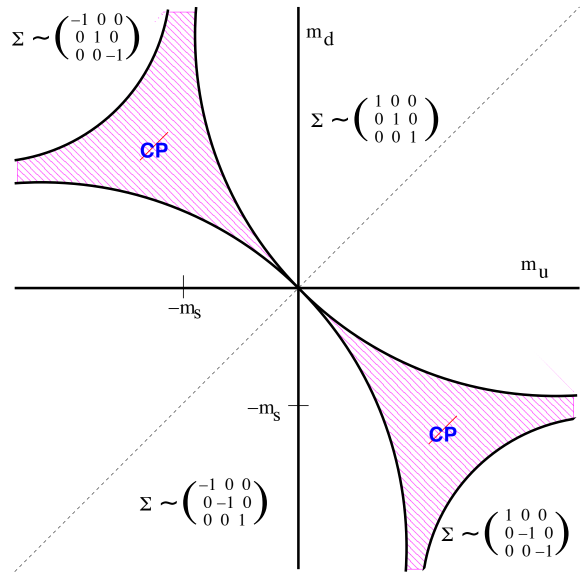
- Lattice world average

- QCD+QED & g-2 LbL
- Proton Decay
- Electric Dipole Moment of Proton/Neutron
- η - η ' Spectroscopy and their Mixing
- Strangeness Contents of Nucleons

Theoretical Studies [M. Creutz]

✓ <u>Phase structure of QCD in (m_u, m_d) plane</u>

[PRD83.016005, Annals. Phys. Phys. 326:911 (2011)]



- Ising-like 2nd order at |mu+md| < |mu-md|
- Phase transition occurs at non-vanishing mu and md
  - Long distance physics without small Dirac eigen values
- No transition at mu=0 when md is non-zero
  - No long distance physics despite small Dirac eigen values

✓ <u>Minimal Doubling Fermions</u>

[PRD83:094506 (2011), JHEP 1012:041, PRD82:074502, JHEP 1009:027 (2010)]

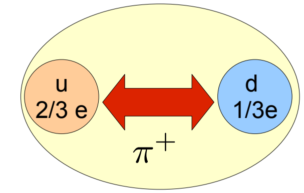
Works with Tatsuhiro Misumi & Taro Kimura
also with Mainz group (Capitani, Wettig et. al.)

✓ <u>Two reviews articles</u>

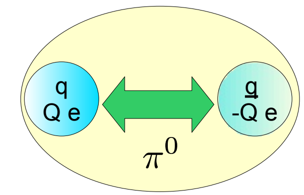
Annals Phys, 324:1573 (2009)
Acta Physica Slovaca 61:1 (2011)

QCD+QED simulation

[PRD 82:094508 (2010), PoS KAON09:034]



(repulsive)



(attractive)

- Breakings of isospin symmetry
  - Electric charge $q_u = +2/3\,e$, $q_d = -1/3\,e$
  - quark masses $m_u \neq m_d$
- Compute Pion/Kaon using Nf=2+1 DWF QCD + QED

  Requiring m_q < 40 MeV (70MeV), 48 (120)
  partially quenched data points for PS meson survive

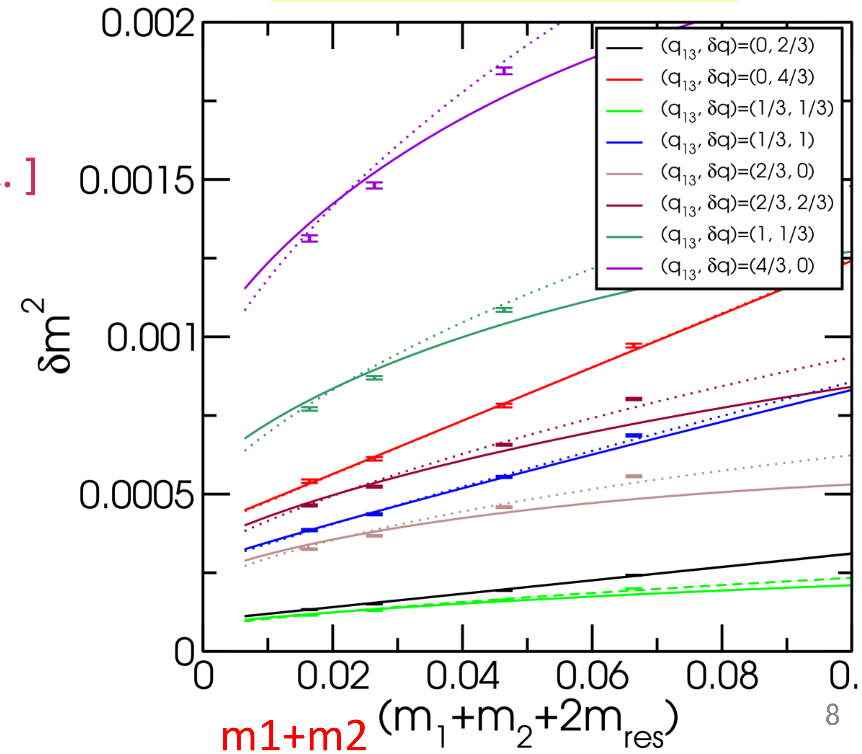
- Fit to chiral perturbation theory with EM (SU(3)+EM or SU(2)+Kaon+EM) to extract quark masses.

  an extension of SU(2)+Kaon ChPT
  [RBC-UKQCD PRD78:114509, PACS-CS, MILC, …]

- Chiral symmetry of DWF is used to define quark massless points.

- Input: experimental data
  M_pi, M_K(+), M_K(0)
- Output: quark masses m_u, m_d, m_s

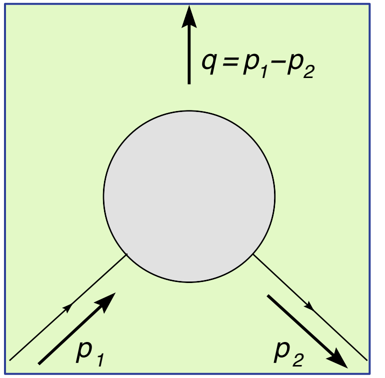
$$M_{PS}^2(e^2) - M_{PS}^2(0)$$



m1+m2

New Renormalization Schemes

[09 C. Sturm, Y. Aoki, N. Christ, TI, C. Sachrajda, A. Soni PRD80:014501 (2009)]



$q^2 = p_1^2 = p_2^2$

- Match the normalization of operator on lattice and in continuum theory (MS) via RI/SMOM schemes

- We find symmetric momentum (SMOM) configuration is useful to reduce one of the dominant systematic errors due to IR effects.

- Quark mass renormalization error

~10% (MOM) → ~ 5% (SMOM) → ~ 2% (SMOM 2-loop) ,

[L. Almeida, C. Sturm, PRD82:054017 (2010)]

- Using different RI/SMOM schemes (using various spinor projections) to check the systematic errors

- 5 different schemes for the four quark operator for B_K to estimate the 2 loop effects.

- Now extended to Delta S = 1 operators (including Delta I = ½)

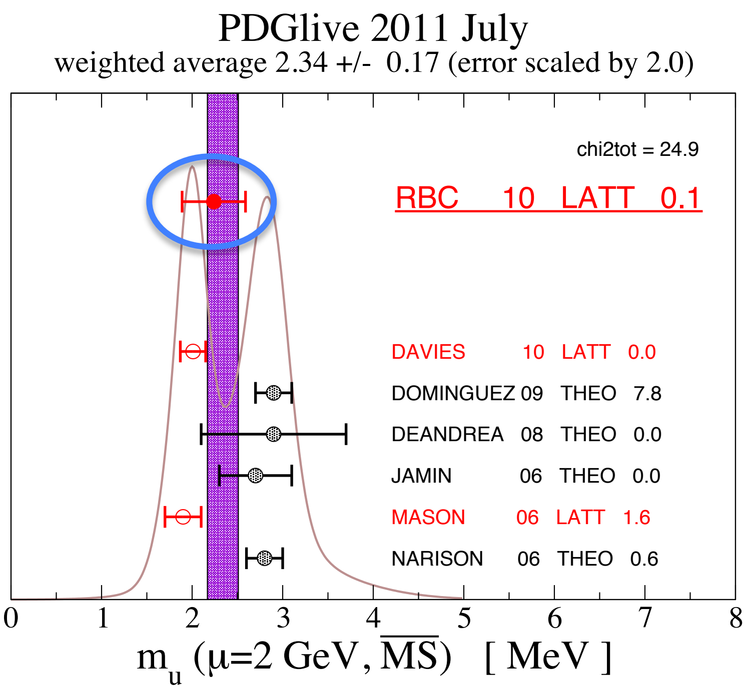
[C. Lehner & C. Sturm, arXiv:1104.4948]

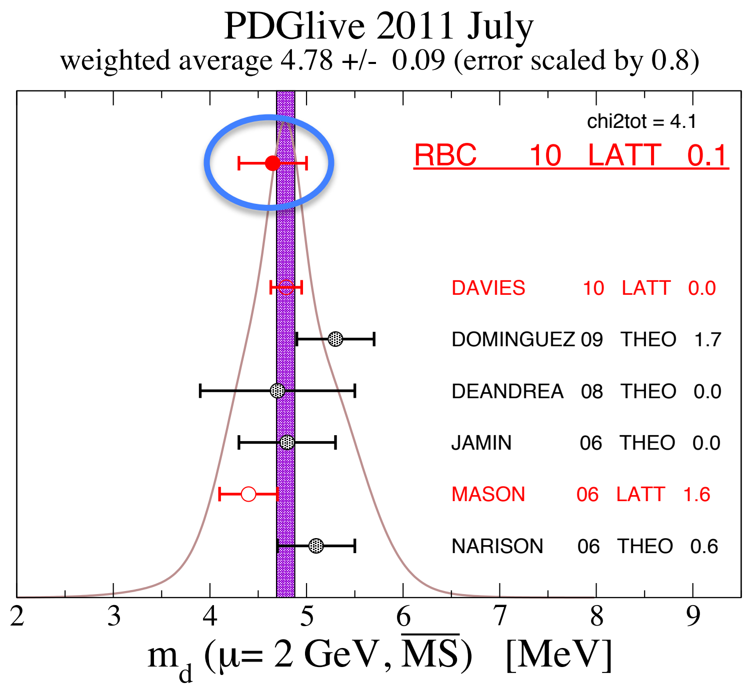
and Step-scaling [R. Arthur & P. Boyle, PRD83 114511 (2011)]

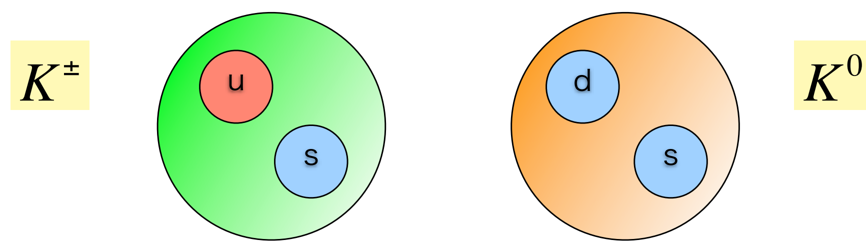
- C. Sturm : an example of cross fields fertilization

The masses of up and down quarks determined are compiled in “Review of Particle Physics” 2011

5 LATTICE (2 DWF + EM and 3 staggered) and 4 THEORETICAL







■ Application of Results :

- Origins of isospin breakings in hadron masses
- Neutron / Proton mass difference
- Breaking of Dashen’s theorem
- Breaking in f_K / f_π, K_{l3}, and Delta I = ½ rule, ε ’/ ε ?

Theoretical Origins of

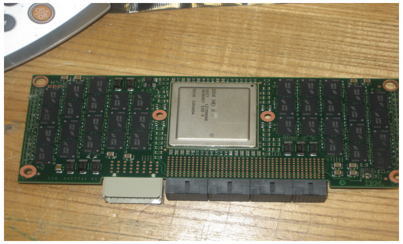
$$M_{K^0} - M_{K^{\pm}} = 3.937(29) \text{ MeV}$$

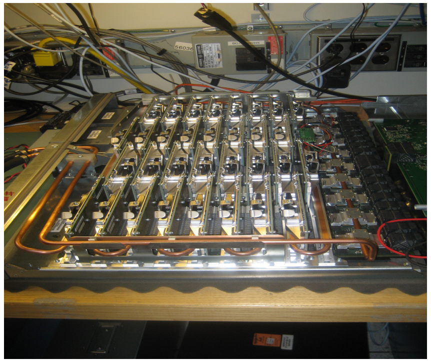
5.23(14) MeV from $(m_d - m_u)$

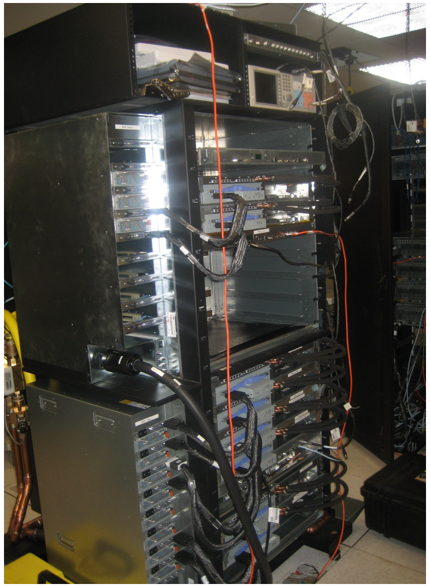
-1.327(37) MeV from QED

QCDCQ (QCD machine for Chiral Quarks)

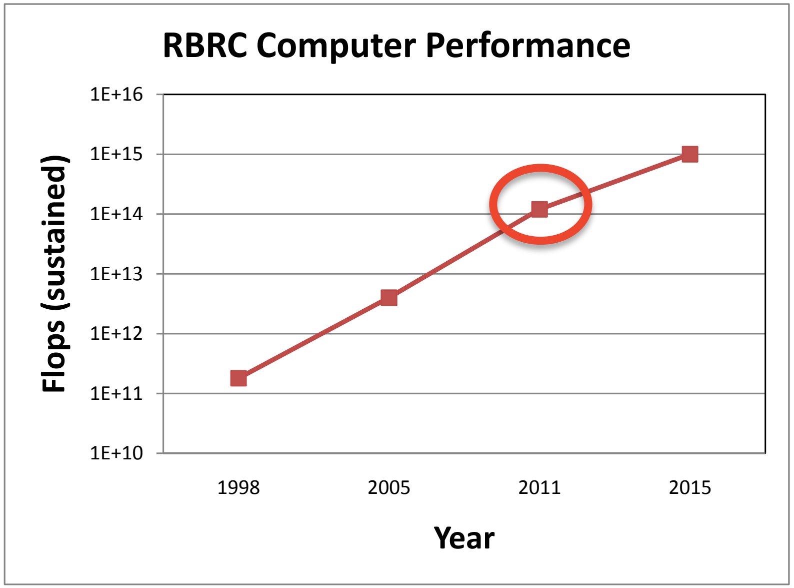
- QCDCQ Computer
  - Successor of QCDSP (99- 1Tflops),
    QCDOC (05- 10Tflops)
  - Pre-commercial machine of IBM's Blue Gene Q, designed & developed by IBM, RIKEN-BNL, Columbia & University of Edinburgh.
    [P. Boyle, N. Christ, C. Jung]
  - 210 T flops peak / rack
  - 2 racks for RIKEN-BNL (DD1) $1M
    1 racks for BNL (DD2) in 2011 $1.5M
    + 1 or 0.5 racks for USQCD ?
  - 4 racks at University of Edinburgh







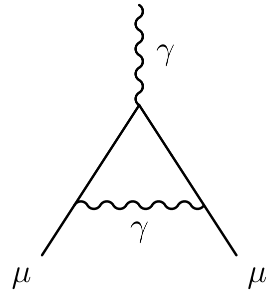
- More accurate calculations
  Mπ = 300 MeV ➔ 180, 135 MeV
  - Improve tests of SM and beyond, CKM, radius of proton, ...
- New calculations will become possible
  - (g-2)_mu LbL, EDM, epsilon'/epsilon, strangeness in Nucleons, ...

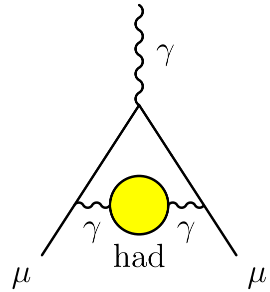


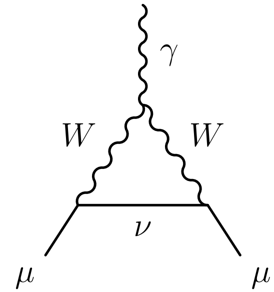
muon's anomalous magnetic moment

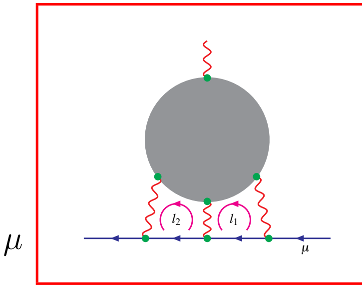
- One of the most precisely determined numbers, starting from the construction of QED.









$$a_\mu = \frac{g-2}{2} = (116\ 592\ 089 \pm 54 \pm 33) \times 10^{-11}$$ BNL-E821

[Andreas Hoecker, Tau 2010, arXiv:1012.0055 [hep-ph]]

Contribution	Result $(\times 10^{-11})$.
QED (leptons)	116 584 718.09 $\pm$ 0.15
HVP (lo)	6 923.$\pm$ 42
HVP (ho)	-97.9 $\pm$ 0.9
HLBL	105.$\pm$ 26
EW	154.$\pm$ 2
Total SM	116 591 802 $\pm$ $42_{\text{HVP(lo)}}$ $\pm$ 26_{HLBL} $\pm$ 02 (49_{tot}).

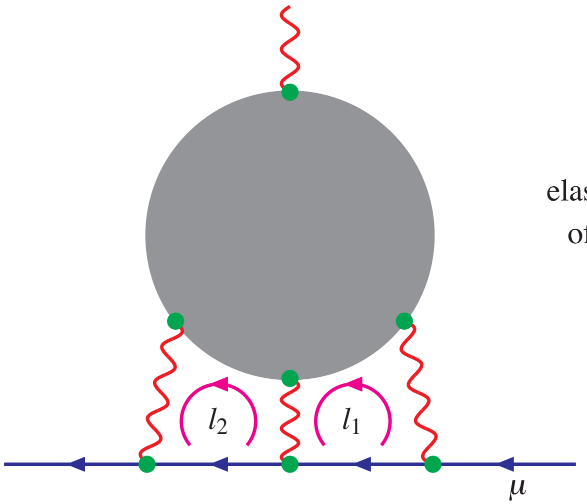
- 287 ± 80 or 3.6σ difference between experiment and SM prediction.

E989 at FNAL is to reduce the total experimental error by, at least, a factor of four over E821, or 0.14 ppm !

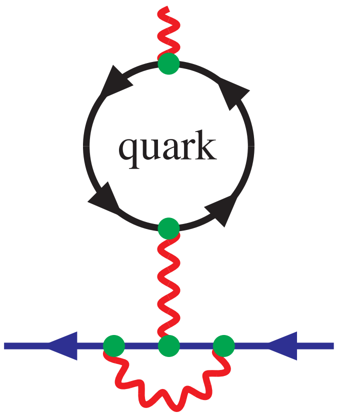
Hadronic Light-by-Light computation on lattice

- Goal : determine HLBL with $\sim$ 10 % accuracy.
  [INT-11-47 Workshop on Hadronic Light-by-Light Contribution to $(g-2)_\mu$ (2011)]

- Direct QCD+QED computation of $(g-2)_\mu$ Hadronic light-by-light diagram.



elastic scattering amplitude of two photons by QCD



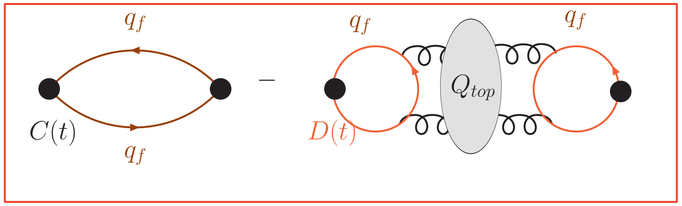
- $\mathcal{O}(e^6)$ two loop QED, l_1 l_2, besides QCD, 8 dimension integral.

- Muon and Photon parts is fully known analytically.

- QCD+QED simulation has unwanted diagrams, which should be taken as parts of the photon's vacuum polarization and the vertex correction. $\mathcal{O}(e^4, e^6)$.

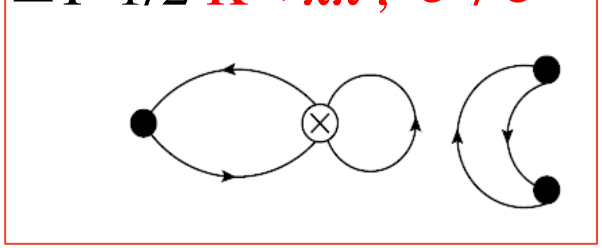
Tackling disconnected quark loops

- Brute force calculation
  Nf=2+1 $\eta - \eta'$ [PRL 100:241601(2010)]



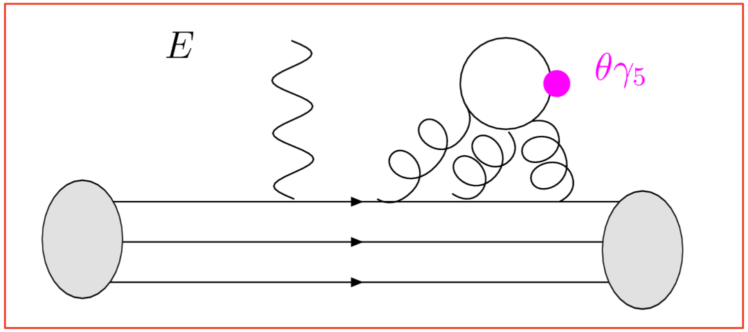
- Optimized (multi) hadron fields
  Direct computation of Re (A_0)

[arXiv:1106.2714 (2011)]



Much improved Re(A_0) and 1st determination of Im(A_0) expected very soon (see Qi Liu's talk@LAT11)

- New Idea Electric Dipole Moment (EDM) of Nucleons



vacuum angle θ is implemented on lattice with analytic continuation

$$\boxed{\theta \rightarrow -i\theta}$$

- New algorithms to accelerate propagator computations
  [EigCG, MaDWF]
  (see B. Mawhinney& H. Yin @ LAT11)
- Improved statistcs by Low eigen-mode averaging

Where are they now ? Lattice

Name	When at BNL	Current Position
Sinya Aoki	1987-89	Faculty at University of Tsukuba
Andreas Gocksch	1988-93	Finance
Aida El-Khadra	1989-91	Faculty at University of Illinois
James Simone (gs; UCLA)	1989-91	Scientist at Fermilab Computer Division
Kenton Yee (gs; UCLA)	1989-92	Lawyer
Claudio Parrinello (gs; Univ. Pisa)	1992-94	Faculty at University of Liverpool
Ivan Horvath (gs; Rochester)	1992-95	Faculty at University of Kentucky
Wendy Schaffer	1993-96	Medicine/Sloane Kettering
Tom Blum	1995-04	Faculty at University of Connecticut
Matt Wingate	1997-00	Faculty at Cambridge University
Chris Dawson	1998-07	Faculty at University of Virginia, Google
Shoichi Sasaki	1998-00	Faculty at University of Tokyo
Tilo Wettig	2000-04	Faculty at Regensburg
Kostas Orginos	2000-03	Faculty at William & Mary
Yasumichi Aoki	2000-03, 2006-2010	Faculty at Nagoya University

gs = graduate student

CWS = Came with own fellowship support

LDRD = Laboratory Directed Research and Development

Where are they now ? Lattice (contd.)

Name	When at BNL	Current Position
Sasa Prelovsek	2001-02	Faculty at Ljubljana
Jack Laiho (gs; Princeton)	2001-04	Faculty at University of Glasgow
Yukio Nemoto	2001-04	Post-doc at Nagoya University
Federico Berruto	2002-04	Finance
Jun-Ichi Noaki	2002-05	Five years fellow at KEK
Takanori Sugihara	2003-05	RIKEN Super computer R&D center
Norikzu Yamada	2003-06	Faculty at KEK
Takashi Kaneko (CWS)	2004-05	Faculty at KEK
Koichi Hashimoto (gs; Kanazawa Univ)	2004-06	HPC Computer Company
Takeshi Yamazaki	2004-07	Faculty at Nagoya University
Takumi Doi	2004-07	Post-doc at University of Tsukuba
Enno Scholz	2005-08	Faculty at Regensburg
Tomomi Ishikawa	2006-09	Post-doc at University of Connecticut
Adam Lichtl	2006-09	Finance

gs = graduate student
CWS = Came with own fellowship support
LDRD = Laboratory Directed Research and Development

Summary

- Lattice QCD is becoming a practical tool for non-perturbative calculation from first principles in particle physics.
  (bridge between experiment and theory)

- DWF, preserves chiral symmetry, is the simplest choice for (Weak) Matrix elements (→ R. Van de Water's talk), which are necessary ingredients for precise checks of the Standard Model of particle physics and beyond.

- DWF Nf=2+1 are being carried out thanks to many developments in theory, hardware, and algorithms.

- New hardware QCDCQ (BG/Q)

- Improved and New Physics quantities :
  - Theoretical analysis
  - Isospin breaking effects from QCD+QED simulation
  - New renormalization schemes RI/SMOM
  - Weak Matrix Elements B_K, ε'/ε, B & D Physics
  - disconnected diagrams η', g-2 LbL, Proton/Neutron EDM, strangeness in Nucleon ...

Appendix

QCDCQ target ensemble

Volume	*1/a*	*L*	m_π	Time units	$m_{quark}a$
32^3 x 64	1.40 GeV	4.5 fm	180 MeV	200	0.001+0.0018
			250 MeV	1000	0.0042+0.0018
24^3 x 64	1.73 GeV	2.7 fm	315 MeV	9000	0.005+0.0032
			402 MeV	9000	0.01+0.0032
32^3 x 64	2.32 GeV	2.7 fm	300 MeV	7000	0.004+0.0006
			350 MeV	8000	0.006+0.0006
			410 MeV	6000	0.008+0.0006

Volume	*1/a*	*L*	m_π	Time units	$m_{quark}a$	QCDCQ Rack Yrs.
48^3 x 64	1.40 GeV	6.7 fm	140 MeV	3000	0.0001+0.0018	0.5
48^3 x 64	2.32 GeV	4.0 fm	180 MeV	6000	0.001+0.0006	0.25
32^3 x 8	1.40 GeV	4.5 fm	140 MeV	200,000	0.0001+0.00018	0.6

QCDCQ target ensemble (contd.)

Volume	$1/a$	L	m_π	Time units	$m_{\mathrm{quark}}a$	QCDCQ Rack Yrs.
$48^3 \times 64$	1.40 GeV	6.7 fm	140 MeV	3000	0.0001+0.0018	0.5
$48^3 \times 64$	2.32 GeV	4.0 fm	180 MeV	6000	0.001+0.0006	0.25
$64^3 \times 128$	2.32 GeV	5.4 fm	140 MeV	6000	0.0004+0.0006	2.5
$32^3 \times 8$	1.40 GeV	4.5 fm	140 MeV	200,000	0.0001+0.0018	0.6
$48^3 \times 8$	1.40 GeV	6.7 fm	140 MeV	200,000	0.0001+0.0018	2.8
$48^3 \times 12$	1.73 GeV	5.4 fm	140 MeV	200,000	0.0005+0.001	2.0

- Coarse and Large lattice for Nucleon Physics and $K \to \pi\pi$ on physical quark mass
- Fine lattice scaling study on physical quark mass for accurate determination for basic quantities.
- Thermo dynamics studies using chiral lattice quark with physical mass.

QCD+QED Other Results

- Breaking of Dashen's theorem (NLO, *O(m e²)*, effects in ChPT)
  [C. Aubin et al. (MILC) PRD70: 114501 (2004)]

$$\Delta E = \frac{M_K^2(m,2/3,m_s,-1/3) - M_K^2(m,-1/3,m_s,-1/3)}{M^2(m,2/3,m,-1/3) - M^2(m,-1/3,m,-1/3)} - 1,$$

$$\boxed{\Delta E = 0.628(59)}$$

(statistical error ony)

- "Iso symmetric QCD" values,
  e=0, at $m_u=m_d=m_{ud}$:

$$\boxed{\begin{aligned} m_\pi^{(\mathrm{QCD})} &= 134.98(23)\ \mathrm{MeV}, \\ m_K^{(\mathrm{QCD})} &= 494.521(58)\ \mathrm{MeV}. \end{aligned}}$$

- Gasser & Leutwyler's Kappa values :

$$\kappa_{\text{quark mass}} \equiv \frac{m_d - m_u}{m_s - m_{ud}} \frac{2m_{ud}}{m_s + m_{ud}} ,$$

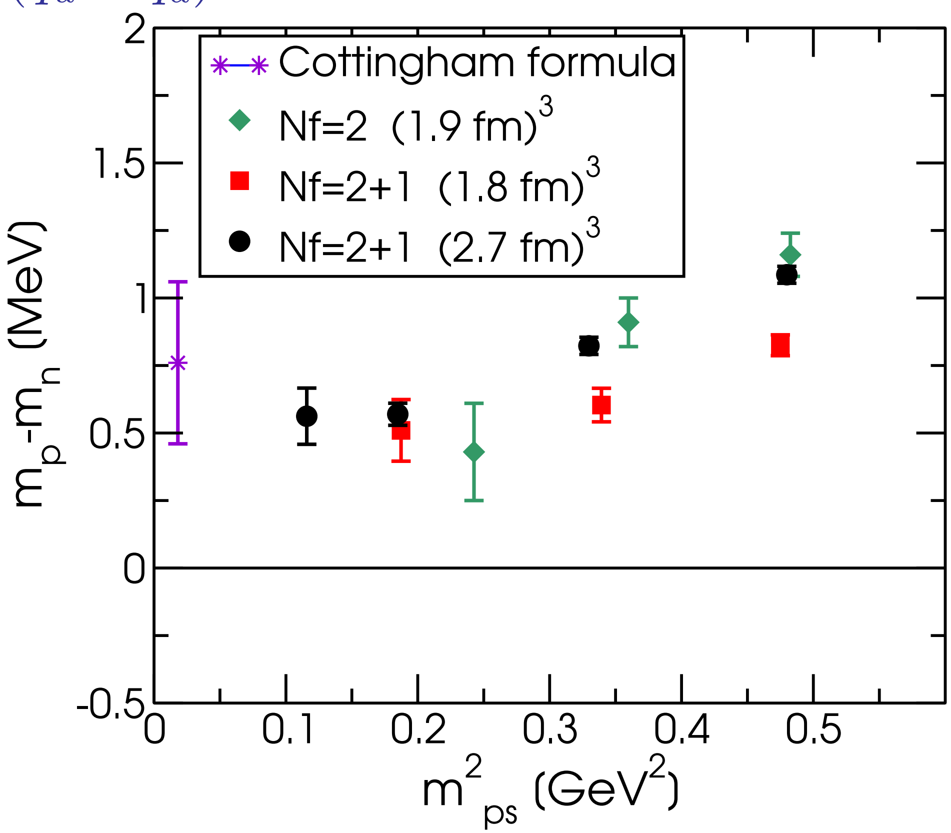
$$\kappa_{\text{meson}} \equiv \frac{(M_{K^0}^2 - M_{K^\pm}^2)_{\mathrm{QCD}}}{M_K^2 - M_\pi^2} \frac{M_\pi^2}{M_K^2}$$

$$\boxed{\begin{aligned} \kappa_{\text{quark mass}} &= 0.00176(4), \\ \kappa_{\text{meson}} &= 0.00191(3), \end{aligned}}$$

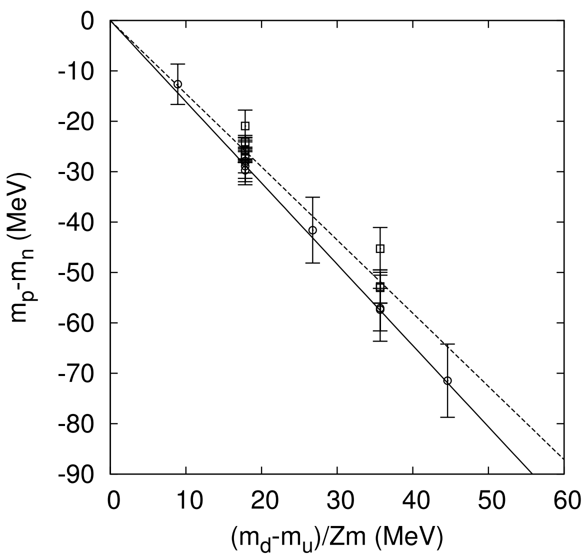
$$\kappa(\eta \to \pi^0\pi^+\pi^-; p^6) = 0.0019(3)$$

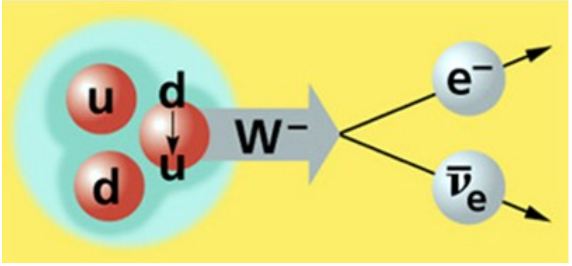
Nucleon mass splitting in $N_F = 2, 2+1$

$(q_u - q_d)$ effect



$(m_{\text{up}} - m_{\text{dwn}})$ effect





$$M_N - M_p|_{\text{QED}} = -0.383(68) \text{ MeV}$$

$$M_N - M_p|_{\text{quark mass}} = 2.24(12) \text{ MeV}$$

$$\Longrightarrow M_N - M_p| = 1.86(14)(47)_{\text{FV,fit}} \text{ MeV}$$

(experiment: $1.2933321(4)$ MeV)

$\mathcal{O}(e)$ error reduction

- On the infinitely large statistical ensemble, term proportional to odd powers of e vanishes. But for finite statistics,

$$\langle O \rangle_e = \langle C_0 \rangle + \langle C_1 \rangle\, e + \langle C_2 \rangle\, e^2 + \cdots$$

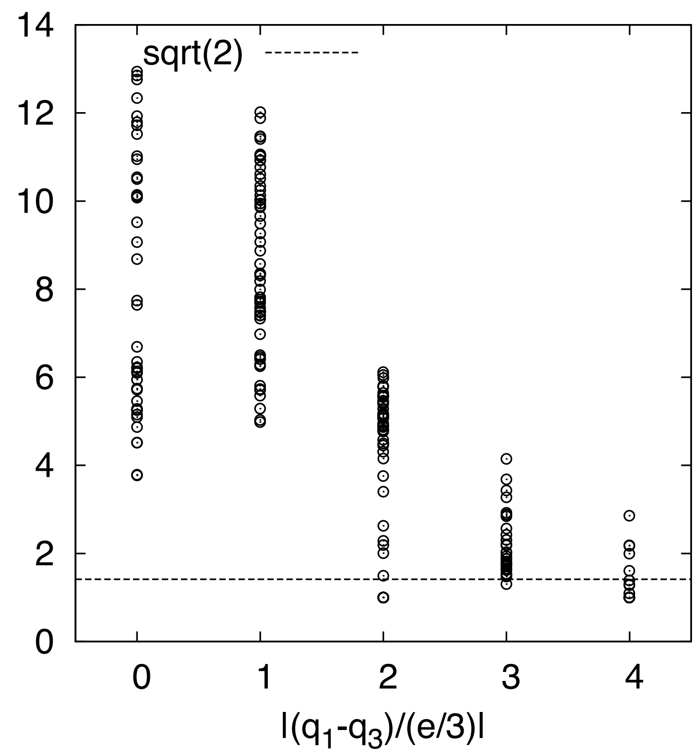
  $\langle C_{2n-1} \rangle$ could be finite and source of large statistical error as e^{2n-1} vs e^{2n}.

- By averaging $+e$ and $-e$ measurements on the same set of QCD+QED configuration,

$$\frac{1}{2}[\langle O \rangle_e + \langle O \rangle_{-e}] = \langle C_0 \rangle + \langle C_2 \rangle\, e^2 + \cdots$$

  $\mathcal{O}(e)$ is exactly canceled.

- More than a factor of 10 error reduction, corresponding to $\times 100$ measurements by only twice computational cost (vs naive reduction factor $\sqrt{2}$).



Other recent works of isospin breaking on lattice

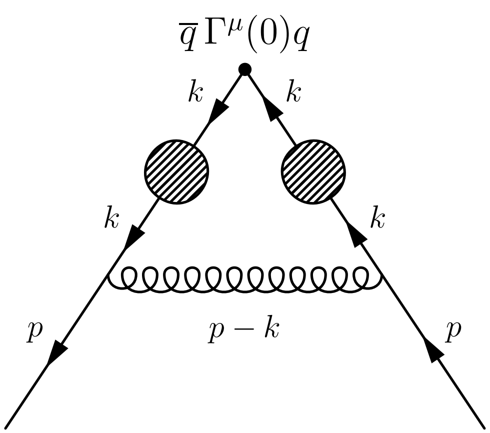
- [A.Portell, LAT10 (BMW)] EM correction to hadron masses
- [A. Torok, LAT10] [E. Freeland, LAT10]
  [MILC Collaboration (S. Basak et al.) PoS LAT2008 127]
  EM splitting using MILC ensembles. The breaking of Dashen's theorem

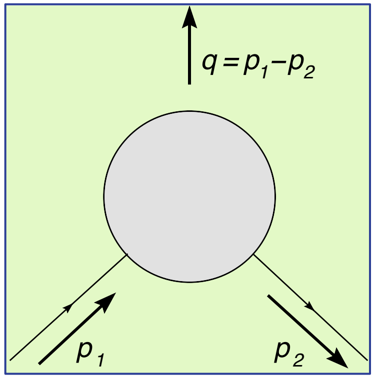
  $$\Delta M_D^2 = (M_{K^\pm}^2 - M_{K^0}^2)_{\text{em}} - (M_{\pi^\pm}^2 - M_{\pi^0}^2)_{\text{em}}$$

- [A. Wallker-Loud, LAT10]
  Using anisotropic clover, $m_u - m_d$ from $m_{\Xi^-} - m_{\Xi^0}$, derive $(m_p - m_n)_{m_d - m_u}$.
- [I.Baum, LAT10]
- [McNeile, Michael, Urbach (ETMC) PLB674(09) 286] $\rho - \omega$ mass splitting using twisted Wilson fermion. Discussed $\rho - \omega$ mixing from $m_u - m_d$. Measure disconnected quark loop correlation.
- [JLQCD (E.Shintani et. al.)PRL 101(08) 242001, PRD79(09)] Calculate $\Pi_V - \Pi_A$, derive the EM contribution to the pion's charge splittings in quark massless limit and the S-parameter using overlap fermion.
- [NPLQCD NPB 768 (07) 38] Calculate $(m_p - m_n)_{m_d - m_u}$. PQChPT for nucleon mass.

RI/SMOM scheme

- Renormalization scale of RI/MOM is set by the momentum of the fermion external lines' p^2
- p^2 has to be large to avoid the unwanted infrared effects from the spontaneous chiral symmetry breaking, absent in the perturbation.
- Exceptional momentum (sum p =0) is easy for perturbation, but has the unwanted effects (Weinberg's theorem). It actually diverges in PS channel (pion pole) at the chiral limit.
- RI/SMOM sets Non-exceptional symmetric momentum configuration, which reduce the unwanted IR divergence. Also perturbative convergence is better to 2 loop.





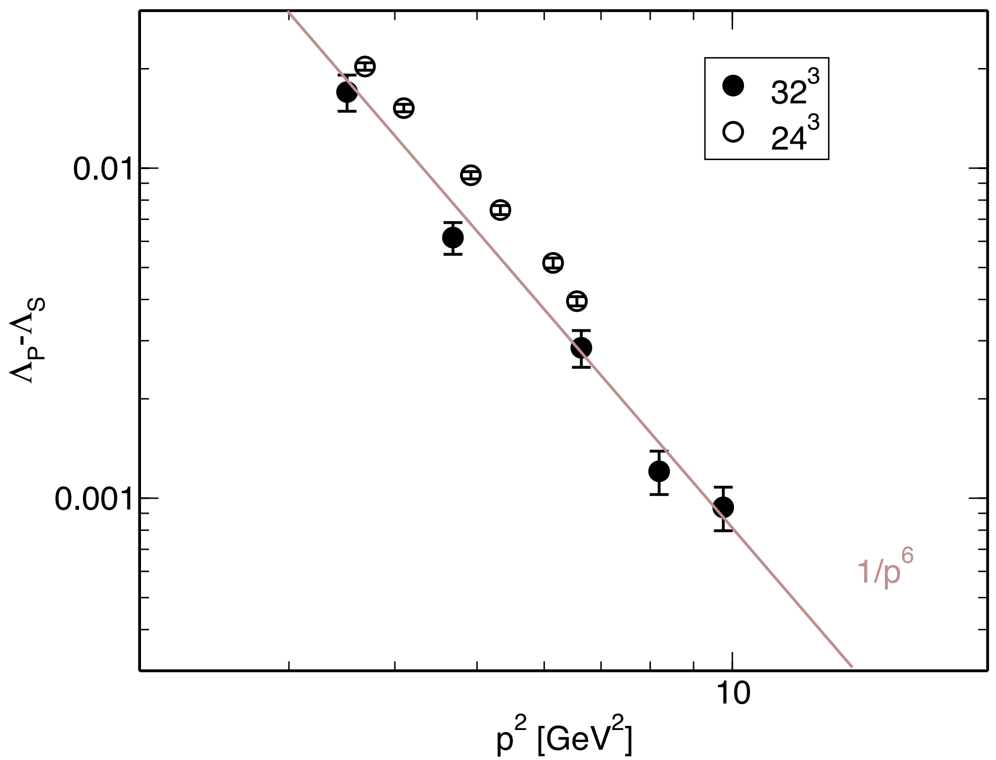
$$q^2 = p_1^2 = p_2^2$$

Results of RI/SMOM

- Residual unwanted effects from chiral symmetry breaking

  ~ 1 % at p = 2 GeV

  [Y. Aoki LAT09]

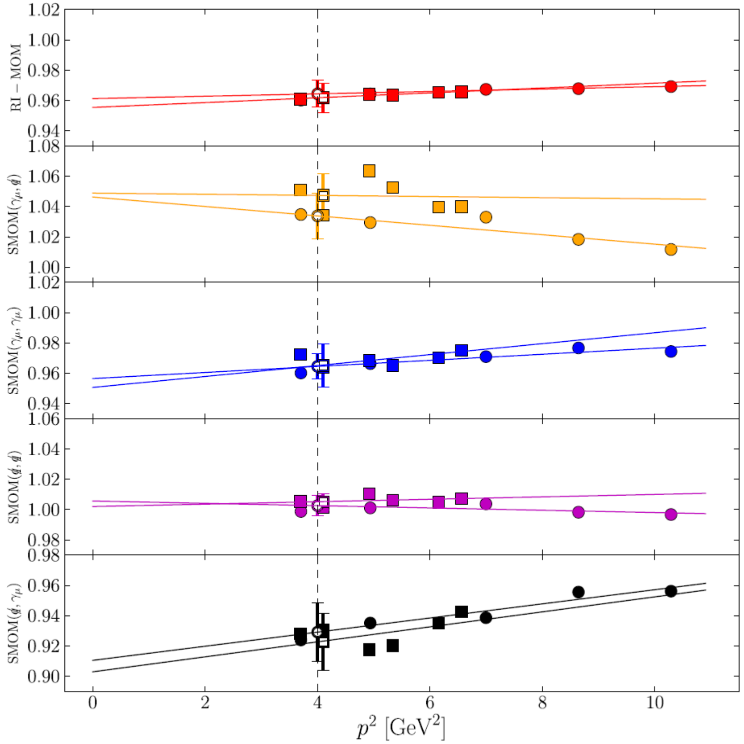


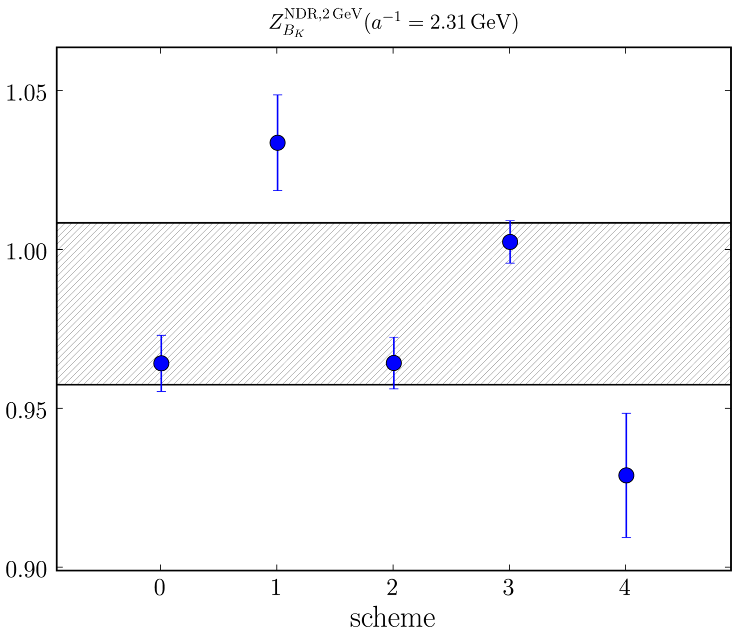
- 2-loop conversion factors. Truncation errors are smaller for SMOM

$$C_m^{\mathrm{RI'/MOM}} = 1 - 0.133 - 0.0759 + \cdots$$
$$C_m^{\mathrm{RI/MOM}_\gamma} = 1 - 0.133 - 0.0816 + \cdots$$

$$C_m^{\mathrm{RI/SMOM}} = 1 - 0.0161 - 0.00660 + \cdots$$
$$C_m^{\mathrm{RI/SMOM}_\gamma} = 1 - 0.0495 - 0.0228 + \cdots$$

Z(BK) systematic errors





$$Z_{B_K}^{NDR}(\mu = 2\mathrm{GeV}, a^{-1} = 2.31\mathrm{GeV}) = 0.964(25)[2.6\%]$$

$$Z_{B_K}^{NDR}(\mu = 2\mathrm{GeV}, a^{-1} = 1.73\mathrm{GeV}) = 0.936(30)$$

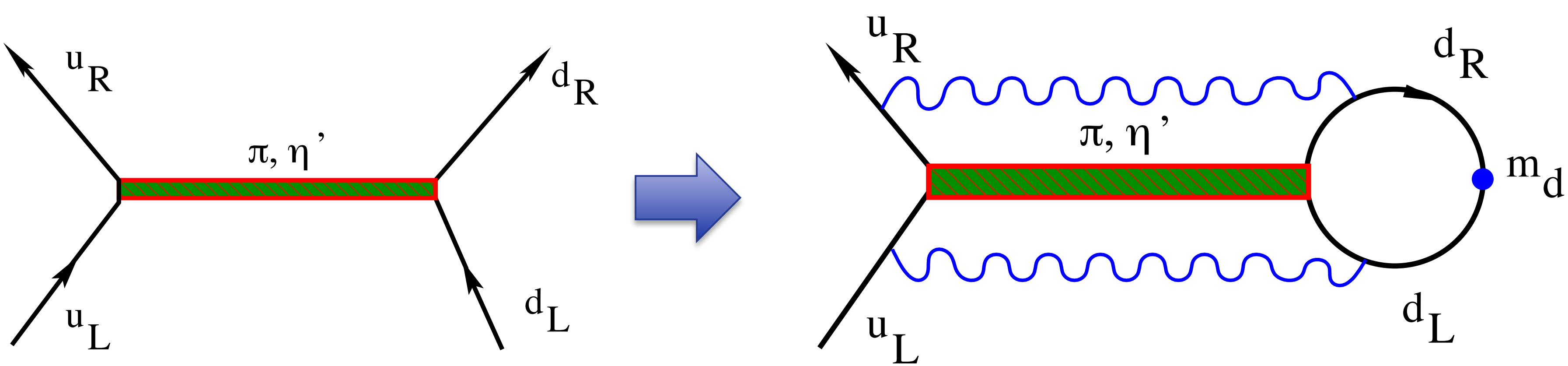
Question about quark masses

[M. Creutz]

- π, η' cause mixing among u_L, u_R, d_L, d_R

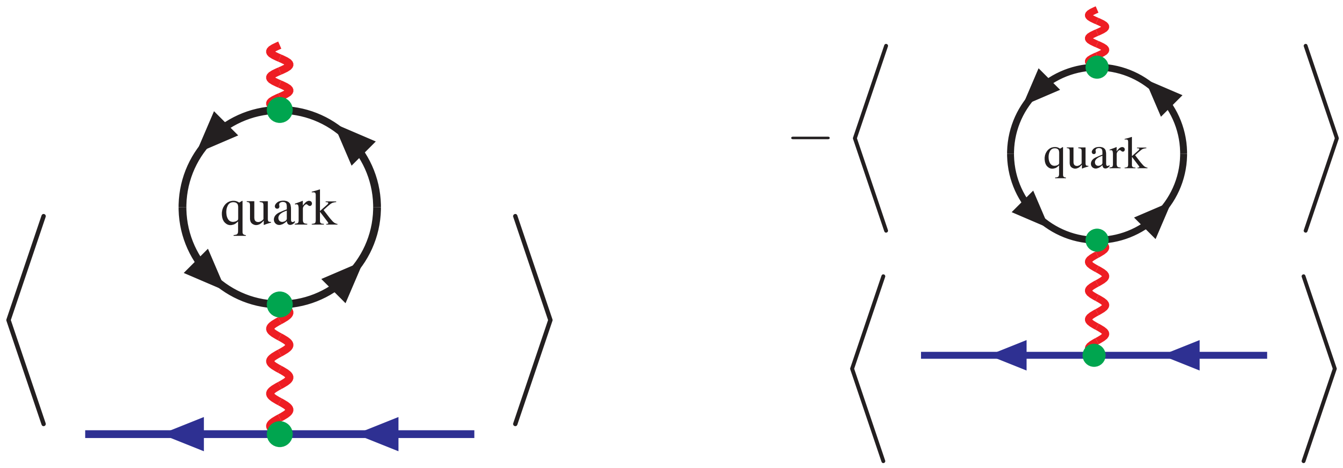
  effect of anomaly 't Hooft vertex

- This may cause an effective RG running for m_u/m_d, and thus scheme dependent.



HLBL subtraction [Lattice2005, hep-lat/050916]

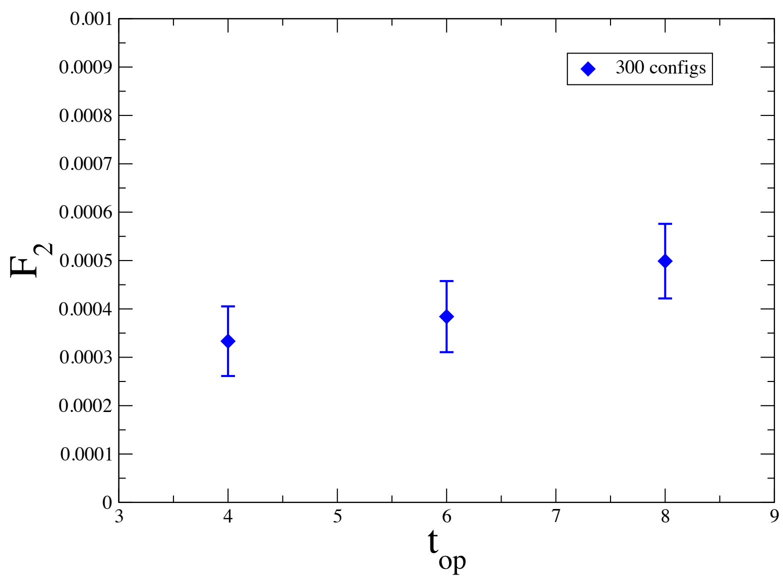
- Use one analytic photon propagator, which help to reduce statistical error from QED.
- Other two photons emerge stochastically (2 stochastic photon propagators).
- Use the parallel 4D FFT.
- In subtracting observables, the up stairs and down stairs are averaged separately, then multiplied together with the analytic photon.
- Correlations between the subtracted and the subtracting help to reduce the statistical error.

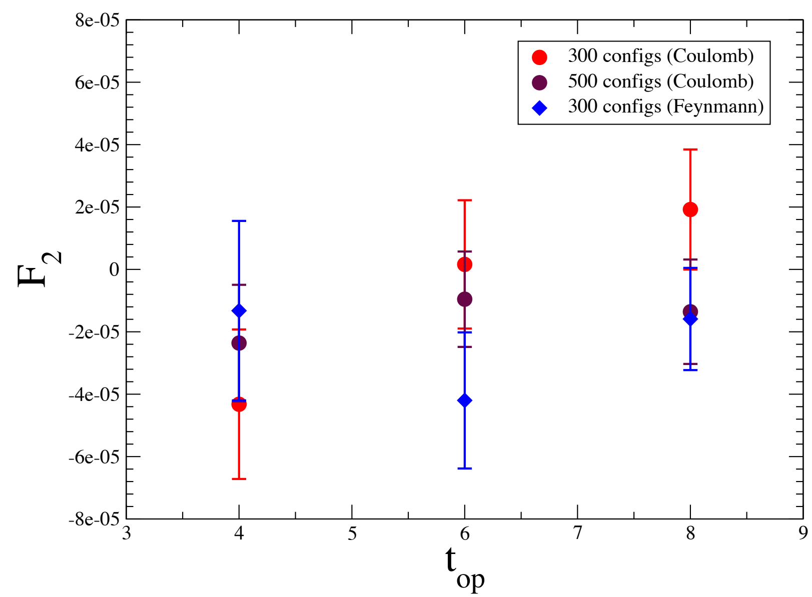


Preliminary Results for QED

[Saumitra Chowdhury Ph.D. thesis+Recent results]

- Only QED ($e = 1$).
- Extract $F_2(q^2)$ from the three point function on $16^3 \times 32$, $L_s = 8$
- $m_\mu = 0.4$ (unphysically heavy), $m_l = 0.01$
- $\mathcal{O}(100 - 1,000)$ QED configurations.





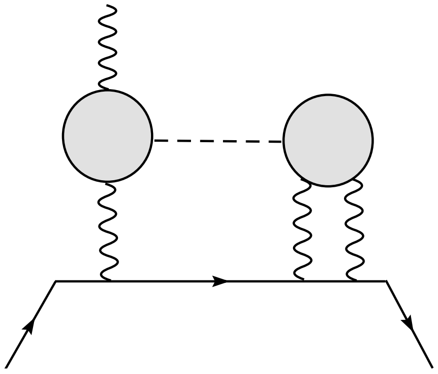
- Non zero signal with a reasonable magnitude is obtained.

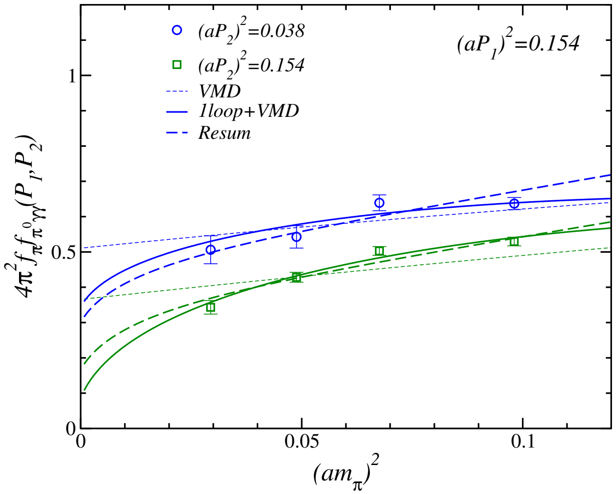
muon's anomalous magnetic moment computation on lattice

- $\pi^0 \to \gamma^{(*)}\gamma^{(*)}$ form factors or transition function [Eigo Shintani] : one of the significant part of HLBL

$$a_\mu^{LbyL} = -e^6 \int \frac{dq_1^4 dq_2^4}{(2\pi)^8} f(q_1, q_2, m_\mu^2) \times \left[\frac{f_{\pi^{0*}\to\gamma^*\gamma^*}(q_1^2, (q_1+q_2)^2) f_{\pi^{0*}\to\gamma^*\gamma}(q_2^2, 0)}{q_2^2 + m_\pi^2}\right] + \cdots$$

$$G_{\mu\nu}^{PVV}(P_2, Q) = \sum_{x,y} e^{-iQx - iP_2 y} \left\langle 2m_q P^3(x) V_\nu^{EM}(y) V_\mu^{EM}(0) \right\rangle$$





K -> π π Decays

- Miani-Testa theorem: Large times yield π π at rest:
  < π π(t) H_W(0) K(-t) > –> <π π(p=0)|H_W|K>.
  - Use finite box with anti-periodic boundary conditions to force $p_\pi \neq 0$.
  - Give the K a finite momentum (Lab frame)
- Lellouch Luscher formula

Relation of on-shell decay amplitude in infinite volume $|A|$(CM) and on finite volume $|M|$(CM)

$$|A|^2 = 8\pi \left(\frac{E_{\pi\pi}}{p}\right)^3 \left\{ p\frac{\partial\delta(p)}{\partial p} + q\frac{\partial\phi(q)}{\partial q} \right\} |M|^2$$

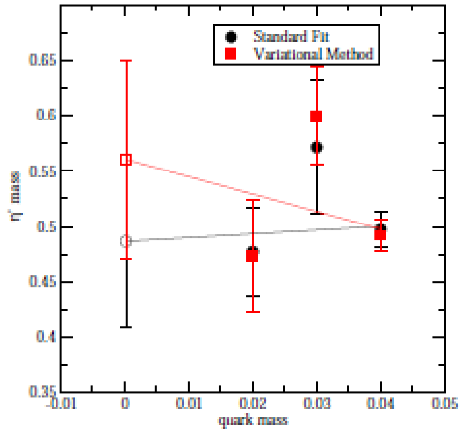
where $E_{\pi\pi} = 2\sqrt{m_\pi^2 + p^2} = m_K$

δ : scattering phase shift

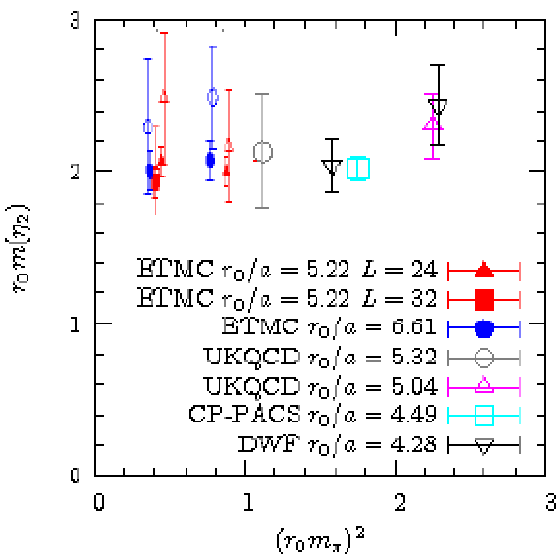
$$\tan\phi(q) = -\frac{q\pi^{3/2}}{Z_{00}(1;q^2)}, \qquad Z_{00}(1;q^2) = \frac{1}{\sqrt{4\pi}} \sum_{n\in\mathbb{Z}^3} \frac{1}{n^2 - q^2}$$

$\delta(p)$ is obtained by $\delta(p) = n\pi - \phi(q),\ q = Lp/2\pi.$ $l > 1$ is neglected.

Eta' results for Nf=2 & 2+1

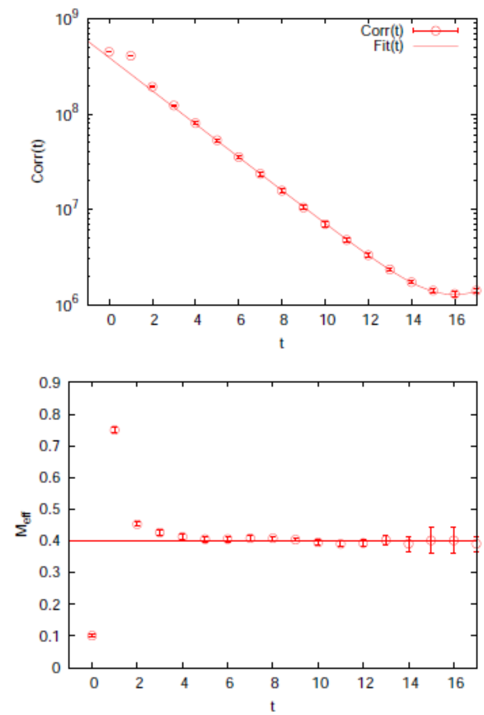


$m_{\eta'}$	$m_{\eta'}^{\text{phys}}$ [MeV]	$m_{\eta'} r_0$	Fit and chiral extrapolation
0.480(78)	738(121)	2.05(33)	(Standard) AWTI
0.487(78)	748(120)	2.08(33)	(Standard) linear
0.532(82)	819(127)	2.28(35)	(Variational) AWTI
0.560(89)	862(130)	2.40(36)	(Variational) linear

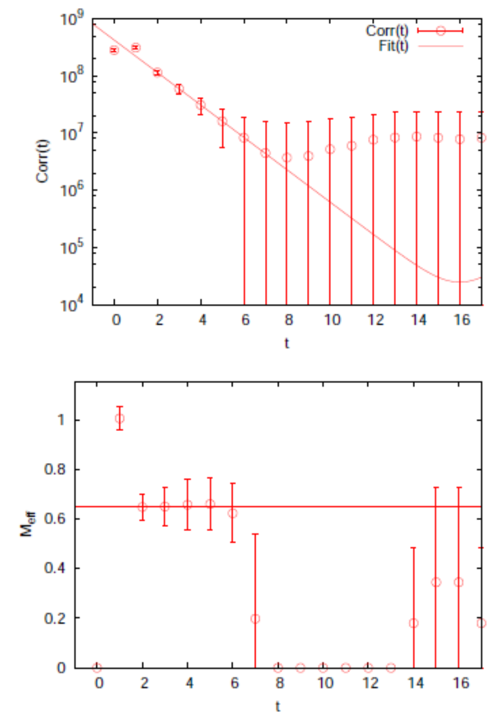


[Nf=2 K. Hashimoto]

$m_\eta = 0.401(11) = 694(19)MeV$



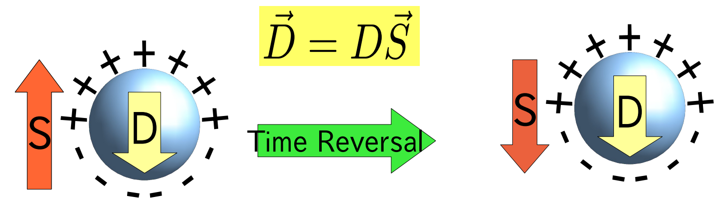
$m_{\eta'} = 0.653(82) = 1.13(14)GeV$



[Nf=2+1 Q. Liu Lattice2009]

Proton/Neutron EDM on Lattice

Permanent Electric Dipole Moment (EDM) is a signature of CP (or Time reversal) symmetry violation.



A source of CP violation：

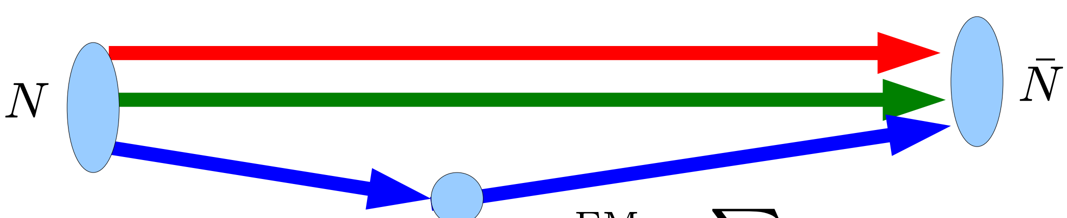
Strong CP: vacuum angle θ , is implemented on lattice with analytically continued to pure imaginary (Monte Carlo simulation)

$$\boxed{\theta \to -i\theta}$$

EDM is measured through the electric form factor $F_3(q^2)$

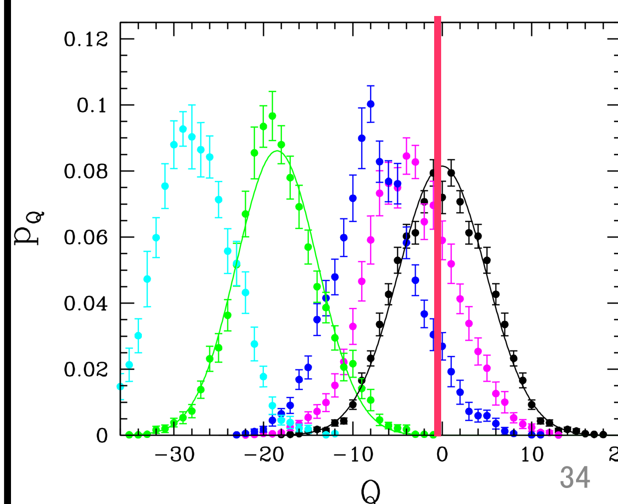
$$D_n = \lim_{q^2 \to 0} \frac{e}{2m_N} F_3(q^2)$$

$$\left\langle N_s(p')|V_\mu^{EM}(q)|\overline{N}_s(p)\right\rangle_\theta = F_1(q^2)\gamma_\mu + F_2(q^2)\frac{q_\nu \sigma_{\mu\nu}}{2m_N} + i\theta F_3(q^2)\frac{q_\nu \sigma_{\mu\nu}\gamma_5}{2m_N} + \cdots, \qquad q = p' - p$$



$$V_\mu^{\mathrm{EM}} = \sum_q e_q \bar{q}\gamma_\mu q$$

$\theta = 1.5, 1.0, 0.4, 0.2, 0.0$

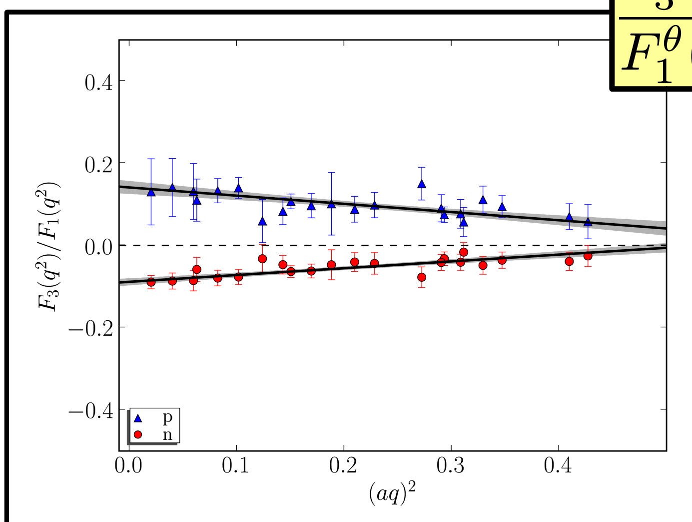


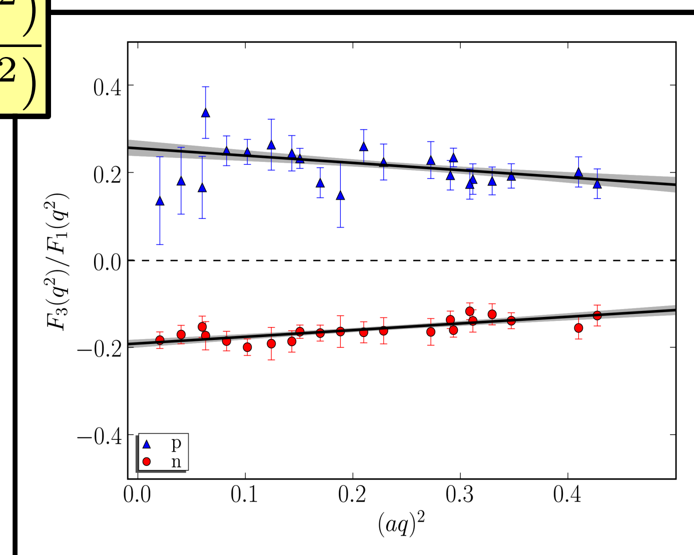
Preliminary Results of NEDM

- θ = 0.2 (left) and θ=0.4 (right)
- Dipole ansatz
- Has the systematical error from chiral breaking of clover fermion.
  [Aoki, Gocksch, Manohar, Sharpe PRL 65 1092 (1990)]
- DWF simulation is planned to remove the lattice artifact.

[arXiv:0808.1428]

$$\frac{F_3^{\theta}(q^2)}{F_1^{\theta}(q^2)}$$





QCD* machines and Blue Gene

- QCDSP (48 GF/rack peak), TI DSP C31 (1993-1998)
  12 racks at RBRC, 600GF

- QCDOC (0.8 TF/rack) 180nm ASIC (2003-2005)
  1 core, System on Chip, 12 racks at RBRC, 10TF,
  $1/Mflops(<u>sustained</u>)

- BG/L (5.7TF/rack) 130nm ASIC (1999-2004)
  dual core system-on chip

- BG/P (13.9 TF/rack) 90nm ASIC (2004-2007)
  quad core, DMA

- QCDCQ (205 TF/rack) 45 nm (2007-2011)
  16 core, $0.02/Mflops(<u>sustained</u>)

- Low power consumptions $\longrightarrow$ large number of nodes (1,024) per rack
- High memory/interconnect Bandwidth
- Gives efficient performance for lattice QCD

Resources

QCDOC (DOE + RBRC) 2005-present 10 + 10 TFLOPS peak

USQCD + other resources (Teragrid, RIKEN/Japan)

2005-2007: 13 TFLOPS (peak) year 1 or 2 proposals to USQCD

Nf=2, 2+1 QCD vacuum, WME, B_K, EM, ...

2008: 80 TFLOPS (peak) year 2 proposals

QCD vacuum + pi,K INCITE ALCF 180 M BG/P core hours (70 TFLOPS year)

2009: 50 TFLOPS (peak) year 4 proposals

QCD vacuum + pi, K INCITE ALCF 78 M BG/P core hours (30+3 TFLOPS year)
Static-B, CPV 10 M QCD node hours (0.93 TFLOPS year)
Relativistic-B 2.6 M 6n-node hours (5.9 TFLOPS year)

2010: 97 TFLOPS (peak) year 7 proposals

QCD vacuum + pi, K INCITE ALCF 75 M BG/P core hour (30+2 TFLOPS year)
EM, Nucleon , Static-B
RICC(RIKEN/Japan) 9.15 M RICC core hours (12 TFLOPS year)
EM, Nucleon RICC 17.4 M RICC core hours (42 TFLOPS year)

Relativistic-B 4 M Jpsi core hours (4 TFLOPS year)

EM 7 M Jpsi core hours (7 TFLOPS year)

Nucleon structures Teragrid (under review)

BG/Q Rack


Capacity for
Four I/O Drawers
Service Card for
Upper Midplane
Bulk Power Supply
Node Card
Service Card for
Lower Midplane
Water Hoses
Another Bulk
Power Supply
(Not Shown)